

Feedback from the IR Background in the Early Universe

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ABSTRACT

It is commonly believed that the earliest stages of star-formation in the Universe were self-regulated by global radiation backgrounds – either by the ultraviolet Lyman–Werner (LW) photons emitted by the first stars (directly photodissociating H_2), or by the X-rays produced by accretion onto the black hole (BH) remnants of these stars (heating the gas but catalyzing H_2 formation). Recent studies have suggested that a significant fraction of the first stars may have had low masses (a few M_\odot). Such stars do not leave BH remnants and they have softer spectra, with copious infrared (IR) radiation at photon energies $\sim 1\text{eV}$. Similar to LW and X-ray photons, these photons have a mean-free path comparable to the Hubble distance, building up an early IR background. Here we show that if soft-spectrum stars, with masses of a few M_\odot , contributed $\gtrsim 1\%$ of the UV background (or their mass fraction exceeded $\sim 90\%$), then their IR radiation dominated radiative feedback in the early Universe. The feedback is different from the UV feedback from high-mass stars, and occurs through the photo-detachment of H^- ions, necessary for efficient H_2 formation. Nevertheless, we find that the baryon fraction which must be incorporated into low-mass stars in order to suppress H_2 -cooling is only a factor of few higher than for high-mass stars.

Key words: cosmology: theory – early Universe – galaxies: formation – molecular processes – stars: Population III

1 INTRODUCTION

In hierarchical models of structure formation, the first stars in the Universe form in dark matter (DM) minihalos with masses of $\sim 10^5 M_\odot$ at redshifts of $z \sim 20 - 30$, through efficient cooling of the gas by H_2 (Haiman, Thoul & Loeb 1996; see a comprehensive review by Barkana & Loeb 2001). However, soon after the first stars appear, early radiation backgrounds begin to build up, resulting in feedback on star-formation. In particular, the UV radiation in the Lyman–Werner (LW) bands of H_2 can photodissociate these molecules and suppress gas cooling, possibly preventing star-formation (Haiman, Rees & Loeb 1997; Omukai & Nishi 1999; Haiman, Abel & Rees 2000; Ciardi, Ferrara & Abel 2000; Machacek, Bryan & Abel 2001; Ricotti, Gnedin & Shull 2001, 2002; Mesinger, Bryan & Haiman 2006; Wise & Abel 2007; O’Shea & Norman 2008; Johnson, Greif & Bromm 2008; Wise & Abel 2008a,b; Whalen et al. 2008; Mesinger, Bryan & Haiman 2009).

Numerical simulations (e.g. Abel, Bryan & Norman 2002; Bromm, Coppi & Larson 2002; Yoshida et al. 2003) have long suggested that the metal-free stars forming in

the early minihalos were very massive ($\sim 100 M_\odot$), owing to the rapid mass accretion enabled by H_2 cooling. These stars would then leave behind remnant BHs with similar masses (Heger et al. 2003), and produce X-rays, either by direct accretion or by forming high-mass X-ray binaries. A soft X-ray background at photon energies of $\gtrsim 1\text{keV}$, at which the early intergalactic medium (IGM) is optically thin, then provides further global feedback: both by heating the IGM, and by catalyzing H_2 formation in collapsing halos (Haiman, Rees & Loeb 1996; Oh 2001; Venkatesan, Giroux & Shull 2001; Glover & Brand 2003; Madau et al. 2004; Chen & Miralda-Escudé 2004; Ricotti, Ostriker & Gnedin 2005; Mirabel et al. 2011).

Recent simulations have been pushed to higher spatial resolution, and in some cases, using sink particles, were able to continue their runs beyond the point at which the first ultra-dense clump developed. The gas in the central regions of at least some of the early minihalos were found to fragment into two or more distinct clumps (Turk, Abel & O’Shea 2009; Stacy, Greif & Bromm 2010; Greif et al. 2011; Clark et al. 2011; Prieto et al. 2011). This raises the possibility that the first stars formed in multiple systems, and that many of these stars had lower masses than previously thought (but see Turk et al. 2012 for still higher

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resolution simulations that suggest less efficient fragmentation).

There is also some observational evidence suggesting a lower characteristic Pop III mass. Massive ($\gtrsim 140 M_{\odot}$), non-rotating metal-free stars are expected to end their lives as pair-instability supernovae (PISNe), and the non-detection of the characteristic PISN nucleosynthetic patterns in metal-poor stars suggests that the typical Pop III stars did not form with such high masses (see, e.g., a recent review by Frebel & Norris 2011). The observations of carbon-enhanced metal poor stars may further imply a significant number of Pop III stars with masses as low as $M = 1 - 8 M_{\odot}$ (Tumlinson 2007b,a). Finally, the recent discoveries of extremely metal poor stars with no sign of C or N enhancement shows that low-mass star formation could occur at metallicities much lower than previously assumed (Caffau et al. 2011, 2012), likely facilitated by dust fragmentation (Schneider et al. 2012).

Motivated by the above, in this *Letter*, we examine radiative feedback from an early cosmic IR background, produced by a population of low-mass stars. Although we focus on low-mass PopIII (i.e., metal-free) stars, our conclusions are more generic, and apply at any cosmic epoch when significant numbers of low-mass PopII stars co-exist with massive PopIII stars. Low-mass stars are expected to have soft spectra, even in the metal-free case (Tumlinson & Shull 2000; Marigo et al. 2001; Schaerer 2002), producing significant radiation at $\sim 1\text{eV}$, near the photo-detachment threshold (0.76 eV) of the H^- ion. H^- is a reactant in the dominant formation channel for H_2 , ($\text{H}^- + \text{H} \rightarrow \text{H}_2 + e^-$) and its destruction can therefore have a dramatic impact on the thermal evolution of metal-free gas.

In fact, it is well known that photo-detachment of H^- by cosmic microwave background (CMB) photons kept the H_2 formation rate in the early Universe very low, until the CMB photons redshifted to lower energies at $z \sim 100$ (Hirasawa, Aizu & Taketani 1969; Hirata & Padmanabhan 2006). H^- photo-detachment can become globally important again once stars begin to form, if they have soft spectra¹.

The aim of this *Letter* is to quantify (i) if and when, due to low-mass stars, H^- photo-detachment again became the dominant process to limit H_2 cooling in the earliest protogalaxies, and (ii) to what extent this may have increased or decreased the net global negative radiative feedback in the early Universe. We focus on the importance of this negative feedback for minihalos (as opposed to the more massive halos that cool even in the absence of molecular hydrogen). In order to accomplish this, we perform “one-zone” calculations, following the coupled chemical and thermal evolution of the gas in the presence of a cosmological radiation background, including H^- photo-detachment by IR photons and H_2 -photodissociation by LW photons.

The rest of this paper is organized as follows. In § 2 we describe our chemical and thermal modeling. In § 3, we present our results for the relative importance of IR radiative feedback, with various assumptions about the stellar populations; we also compare our results to previous studies. Finally, in § 4 we offer our conclusions. Throughout

this paper we adopt a standard ΛCDM cosmological background model: $(\Omega_{\text{DM}}, \Omega_{\text{b}}, \Omega_{\Lambda}, h) = (0.233, 0.046, 0.721, 0.701)$ (Komatsu et al. 2011).

2 MODELING

2.1 Background Spectrum

We assume that the early Universe is filled with background radiation produced by stars. Massive metal-free stars have hard spectra, with effective blackbody temperatures of $T_{\text{eff}} \approx 10^5\text{K}$ on the zero-age main sequence (ZAMS), nearly independent of their mass above $M_{\star} \gtrsim 100 M_{\odot}$ (Marigo et al. 2001; Bromm, Kudritzki & Loeb 2001; Schaerer 2002). Below this mass, the effective temperature decreases monotonically, and reaches $T_{\text{eff}} \approx 10^4\text{K}$ at $M_{\star} \approx 2 M_{\odot}$ (Tumlinson & Shull 2000; Marigo et al. 2001; Schaerer 2002).

We first consider a composite spectrum produced by co-existing low- and high-mass stars, the relative abundances of which are allowed to vary. We choose characteristic masses of $M_{\text{lo}} = 1.2 M_{\odot}$ and $M_{\text{hi}} = 100 M_{\odot}$, which have time-averaged effective temperatures of $T_{\text{eff,lo}} = 10^{3.95}\text{K}$ and $T_{\text{eff,hi}} = 10^{4.88}\text{K}$, respectively (Marigo et al. 2001). These stars have main sequence lifetimes of $t_{\text{ms}} \approx 3\text{Gyr}$ and $\approx 3\text{Myr}$. In our analysis below, for low-mass stars with $t_{\text{ms}} < 0.5\text{Gyr}$ (the age of the universe at $z \approx 10$), we reduce the total radiative output by the factor $(t_{\text{ms}}/0.5\text{Gyr})$. We parameterize the population by the mass fraction of low-mass stars, $f_{\text{lo}}^{\text{mass}}$ and also by their corresponding fractional contribution $f_{\text{lo}}^{\text{uv}}$ to the total UV radiation output (at 13.6eV).

We caution that this is of course only a crude characterization of the true background - in principle, one needs to consider the time-evolving spectra of stars with a range of initial masses. Departures from a black-body shape may also be important, as our results are sensitive to photons with the particular energies of $\sim 2\text{eV}$ (for H^- detachment) and $\sim 12\text{eV}$ (for H_2 dissociation). However, given that the stellar IMF is unknown, we here adopt this simple prescription and defer a more detailed treatment to future work. In order to understand the dependence on stellar mass, in § 3.2 we repeat our calculations assuming the background is produced by stars with a single mass in the range $0.7 \leq M_{\text{char}}/M_{\odot} \leq 100$ (corresponding to effective temperatures in the range $6000 \lesssim T_{\text{eff}} \lesssim 10^5\text{K}$).

The early IGM is optically thin at the IR energies of $\sim 2\text{eV}$, relevant for photo-detachment of H^- (owing to the very low abundance of both intergalactic H^- and of e^-). However, before reionization, the IGM is opaque above 13.6eV, and we accordingly assume zero flux above this energy. UV photons in the LW bands (11.2-13.6eV), traveling over cosmological distances, will also be absorbed by HI once they redshift into resonance with a Lyman line. This results in a “sawtooth modulation” (Haiman, Rees & Loeb 1997), which reduces the H_2 dissociation rate by about an order of magnitude at $z = 15$ compared to the optically thin rate (Wolcott-Green & Haiman 2011). We include this reduction in our calculation. In principle, the optical depth in the LW lines due to intergalactic H_2 itself, with an abundance of $n_{\text{H}_2}/n_{\text{H}} \sim 10^{-6}$, can be of order a few (Haiman, Abel & Rees 2000; Ricotti, Gnedin & Shull 2001;

¹ To our knowledge, this point was first noted and discussed by Chuzhoy, Kuhlen & Shapiro (2007); see § 3.3 below.

Kuhlen & Madau 2005); this additional opacity could further reduce the H_2 -dissociation rate and would strengthen our conclusions; we conservatively ignore it in our calculations.

2.2 Chemistry and Cooling

We model a static gas cloud which has condensed to the maximum density achievable by adiabatically collapsing in a minihalo with virial temperature T_{vir} : $\rho_{\text{max}} = f_\rho \rho_{\text{IGM}} (T_{\text{vir}}/T_{\text{IGM}})^{3/2}$. Here ρ_{IGM} and T_{IGM} are the density and temperature of the smooth background IGM, and f_ρ (chosen below) is of order unity and is used for calibration against simulations. At this stage, only if sufficient H_2 forms will the cloud be able to radiatively cool and continue collapsing to higher densities, and ultimately form stars.

We follow the chemical and thermal evolution for primordial gas, using a standard chemical reaction network among nine species: H , H^+ , H^- , He , He^+ , He^{2+} , H_2 , H_2^+ and e^- (and photons). Radiative cooling by H_2 is modeled as in Galli & Palla (1998). Our chemical model is adopted from Shang, Bryan & Haiman (2010), where the reader is referred for more details and references. We adopt initial conditions appropriate for a minihalo (i.e. with molecular hydrogen and electrons fractions of $x_{\text{H}_2} = 2 \times 10^{-6}$ and $x_e = 10^{-4}$, and initial gas temperature $T_{\text{gas}} = T_{\text{vir}} = 400\text{K}$). We follow the coupled thermal and chemical evolution using the stiff equation solver LSODAR for $\approx 10^8$ years (or ~ 20 per cent of the Hubble time at $z \sim 10$, after which it is likely the halo will have merged with another to form a larger collapsed object).

Photo-detachment of H^- by continuum photons ($\text{H}^- + \gamma \rightarrow \text{H} + e^-$) is dominated by $\sim 2\text{eV}$ photons (at which the H^- detachment rate peaks for $T_{\text{eff}} \approx 10^4\text{K}$, slightly above the 0.755eV threshold). We fit the frequency-dependent cross-section as in Shapiro & Kang (1987), convolving this with the blackbody spectrum to find the rate coefficient, parameterized as $k_{25} = 10^{-10} \alpha J_{21} \text{ s}^{-1}$. Here and below, J_{21} denotes the specific intensity at the Lyman limit (13.6eV) in units of $10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$. For the composite spectrum with $(T_{\text{eff,lo}}, T_{\text{eff,hi}}) = (10^{3.95}\text{K}, 10^{4.88}\text{K})$, we have $\alpha = \alpha_{\text{lo}} f_{\text{lo}}^{\text{uv}} + \alpha_{\text{hi}} (1 - f_{\text{lo}}^{\text{uv}})$, and $(\alpha_{\text{lo}}, \alpha_{\text{hi}}) = (10^4, 0.17)$.

For the photodissociation of H_2 by LW photons we use the fitting formulae for the optically-thick rate provided by Wolcott-Green, Haiman & Bryan (2011), which includes self-shielding as well as shielding by HI . The column densities are specified by assuming the size of the collapsing region equals the Jeans length; however, we reduce N_{H_2} by a factor of 10, which produces better agreement with the shielding found in three-dimensional simulations (Wolcott-Green, Haiman & Bryan 2011).

3 RESULTS AND DISCUSSION

3.1 Composite Spectrum

The Critical Flux

To assess whether H_2 -cooling can be suppressed by the IR background, we first run one-zone models at various different radiation intensities, normalized at the Lyman-limit

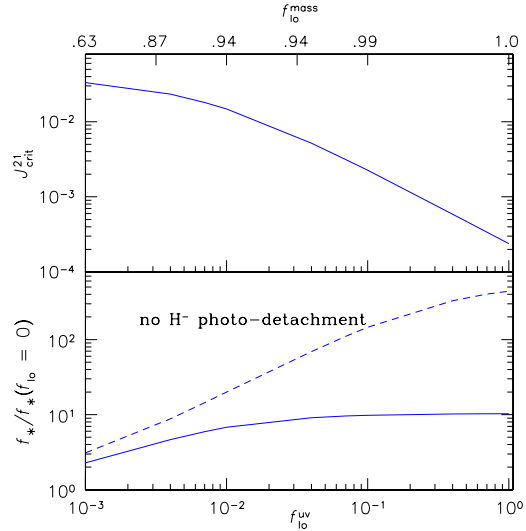


Figure 1. *Top panel:* The critical flux J_{crit}^{21} required to suppress H_2 -cooling as a function of $f_{\text{lo}}^{\text{uv}}$. Here $f_{\text{lo}}^{\text{uv}}$ is a proxy for the fraction of the Lyman limit flux contributed by low-mass stars with an effective temperature $T_{\text{eff}} \approx 10^4\text{K}$ (rather than high-mass stars with $T_{\text{eff}} \approx 10^5\text{K}$). The corresponding mass fraction in the low-mass stars, $f_{\text{lo}}^{\text{mass}}$, is shown along the upper horizontal axis. *Bottom panel:* The fraction of baryons that must be converted into stars in order to produce the critical flux shown in the top panel (solid line). Also shown is the required fraction if H^- photo-detachment is artificially switched off in the chemistry network (dashed line).

J_{21} . We employ a Newton-Raphson scheme to find the “critical flux,” J_{crit} , defined by requiring that the cooling time always remains longer than the dynamical time (eq. 10 in Haiman, Rees & Loeb 1997). Repeating this calculation for halos with different masses and redshifts, we have found that with the density normalization $f_\rho = 0.5$, our resulting $J_{\text{crit}} = J_{\text{crit}}(M_{\text{halo}}, z)$ agrees well (to within a factor of two) with the values, and the mass- and redshift-dependence of J_{crit} found in simulations (Machacek, Bryan & Abel 2001; Mesinger, Bryan & Haiman 2006). Throughout this section, we show our results for a single halo mass scale, $T_{\text{vir}} = 400\text{K}$ and redshift $z = 18$ (corresponding to the lowest-mass minihalos that can cool via H_2). Apart from a monotonic overall increase of J_{crit} with T_{vir} and with z , our results are qualitatively the same for other redshift and halo masses (up to the scale corresponding to $T_{\text{vir}} \sim 10^4\text{K}$, at which atomic cooling becomes important).

Our main result is shown in Figure 1, the top panel of which shows the critical flux J_{crit} as a function of $f_{\text{lo}}^{\text{uv}}$ (the corresponding mass fraction $f_{\text{lo}}^{\text{mass}}$ is shown along the upper horizontal axis). The critical flux decreases dramatically as $f_{\text{lo}}^{\text{uv}}$ increases above the per cent level. Since the normalization of the critical flux is quoted at 13.6eV , close to the LW band, the critical LW dissociation rate would be nearly independent of $f_{\text{lo}}^{\text{uv}}$; the decrease is caused entirely by the H^- detachment by IR photons. The IR radiation becomes more important than the LW radiation when the decrease reaches a factor of two, which occurs for $f_{\text{lo}}^{\text{uv}} \approx 10^{-2}$. However, because the low-mass stars emit far fewer Lyman-limit photons than those with effective temperatures $\sim 10^5\text{K}$, a mass fraction of $f_{\text{lo}}^{\text{mass}} \approx 0.9$ is required to achieve even

this percent level contribution to the flux (as shown by the upper horizontal axis). For reference, the mass fraction of stars in the $0.1\text{--}1.2M_{\odot}$ ($0.1\text{--}2M_{\odot}$) range for the commonly used Chabrier IMF is 86% (94%). In the limit of purely low-mass stars, J_{crit} is decreased by a factor of ≈ 150 . (Note that Clark et al. 2011 do find the protostellar IMF peaked at $\lesssim 1M_{\odot}$, but ZAMS masses are unknown.)

Global Impact

We next ask whether the critical flux $J_{\text{crit}} = \text{few} \times (10^{-4} - \times 10^{-2})$ can be produced by the mixture of high- and low-mass stars. To answer this, we determine the fraction of baryons that must be incorporated into stars to produce a given J_{crit} , as a function of $f_{\text{lo}}^{\text{uv}}$. The energy density in LW photons $u_{\gamma} \simeq 4\pi\nu J_{\text{crit}}/c$ is converted to a stellar mass density ρ_{\star} by computing the number of LW photons emitted per stellar baryon.² We use the data from Marigo et al. 2001 for this purpose, and find the mass-weighted average for the high- and low-mass populations.

The bottom panel of Figure 1 shows the critical baryon fraction, $f_{\star, \text{crit}}$, which must be incorporated into stars to achieve $J_{\text{crit}}(f_{\text{lo}}^{\text{uv}})$ (normalized to its value in the absence of any low-mass stars). The fraction varies relatively little over the range $0 \leq f_{\text{lo}}^{\text{uv}} \leq 1$ (solid curve). The factor of ~ 10 increase as $f_{\text{lo}}^{\text{uv}} \rightarrow 1$ is due almost entirely to the long lifetimes of the low-mass stars, and the corresponding reduction of their radiation output over the finite 0.5 Gyr age of the universe (at $z \approx 10$). The otherwise near-flatness of this curve is a coincidence: increasing $f_{\text{lo}}^{\text{uv}}$ decreases both the critical flux and the production of LW photons per stellar mass, and these two factors turn out to nearly cancel. The bottom-line is that H^{-} photo-detachment can indeed suppress subsequent star formation; this requires converting baryons into low-mass stars up to an order of magnitude more efficiently than in the high-mass case. Finally, the dashed curve in the bottom panel in Figure 1 shows that if the IR photons from the low-mass stars were neglected, the required stellar density would increase by two orders of magnitude. This highlights the importance of including IR feedback in future models if the Pop III IMF indeed extends to such low masses (and also at all cosmic epochs when PopII stars are already present).

3.2 Dependence on effective temperature

How low do the masses of low-mass stars need to be before IR feedback becomes important? To answer this question, we next consider stellar populations with a single effective temperature, in the range $6000 \lesssim T_{\text{eff}}/\text{K} \lesssim 10^5$, and compute how J_{crit} and $f_{\star, \text{crit}}$ depend on T_{eff} . The top panel of Figure 2 shows a dramatic drop in the critical flux owing to the copious $\sim 2\text{eV}$ photon output below $T_{\text{eff}} \approx 1.5 \times 10^4\text{K}$, or $M \lesssim 2M_{\odot}$. As shown in the bottom panel of this figure, the density in stars required to produce J_{crit} remains essentially constant down to this T_{eff} , and very near the value required for LW feedback by high-mass stars. This flatness again results from the cancellation of two effects: the critical flux and the LW photon output (per stellar baryon) both decrease significantly as T_{eff} drops below $1.5 \times 10^4\text{K}$.

² We assume a flat spectrum across the narrow LW bands; the “sawtooth modulation” by the IGM has been absorbed into J_{crit} .

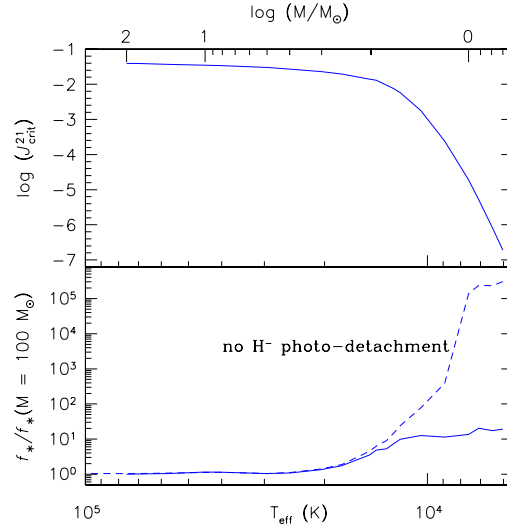


Figure 2. *Top panel:* Critical flux normalized (as in Fig. 1) at the Lyman limit, as a function of effective temperature of the incident blackbody radiation. The corresponding masses of zero-metallicity stars, shown along the upper horizontal axis, are obtained from the data tables provided by Marigo et al. (2001). *Bottom panel:* The fraction of baryons that must be incorporated into stars in order to produce the critical flux in the top panel.

3.3 Comparison to previous studies

To our knowledge, the dominant importance of the radiation from low-mass stars for global star-formation was not previously discussed or quantified, with the exception of Chuzhoy, Kuhlen & Shapiro (2007). These authors evaluated the global impact of H^{-} -detachment by an IR background at later epochs, produced by recombination radiation as the IGM is becoming significantly ionized (Glover 2007 considered a similar scenario, with radiation from gas that is highly ionized by local sources). They showed that if the ionization is produced by stars with a soft spectrum, as we consider here, the H^{-} -detachment rate can be further boosted and can become globally important. However, they do not explicitly compare H^{-} and LW feedback, and do not answer the two questions addressed in this *Letter*: how many low-mass stars need to form (1) before H^{-} photo-detachment becomes the dominant feedback mode, and (2) for this mode to become globally important.

Other previous works have touched on different aspects of the global radiative feedback discussed here. Examples include Mesinger, Bryan & Haiman (2006) and Mesinger, Bryan & Haiman (2009), studying radiative feedback in a statistical sample of several hundred early minihalos in cosmological simulations; Haiman, Abel & Rees (2000) and Johnson, Greif & Bromm (2008), studying self-regulation of star-formation in minihalos through radiative feedback in semi-analytical models; and Whalen, Hueckstaedt & McConkie (2010), studying radiative feedback in detailed hydrodynamical simulations with the stellar masses of the sources extending down $25 M_{\odot}$. However, in all of these works, feedback was due to Lyman-Werner (or ionizing UV) radiation.

Omukai (2001), Bromm & Loeb (2003), Shang, Bryan & Haiman (2010), Wolcott-Green & Haiman

(2011) and Wolcott-Green, Haiman & Bryan (2011) have performed calculations similar to the one proposed here, including H^- photo-detachment, but have focused on the more massive ($T_{\text{vir}} > 10^4 \text{K}$) atomic-cooling halos. Because the gas in these halos can cool via neutral H and reach high densities, a much larger flux J_{crit} is required to suppress H_2 -cooling. Nevertheless, these works have found results similar to the ones here: the critical flux for a soft spectrum is $\sim (1 - 2)$ orders of magnitude lower than for a hard spectrum. For example, using 3D simulations of three different halos, Shang, Bryan & Haiman (2010) found $30 < J_{\text{crit}} < 300$ ($T_{\text{eff}} = 10^4 \text{K}$) versus $10^4 < J_{\text{crit}} < 10^5$ ($T_{\text{eff}} = 10^5 \text{K}$). As found here, H^- -detachment dominates in the former case, whereas H_2 -dissociation dominates in the latter. When self-shielding in the LW lines of H_2 is modeled more accurately, however, this difference is reduced by about an order of magnitude (Wolcott-Green, Haiman & Bryan 2011).

4 CONCLUSIONS

The main conclusion of this *Letter* is that if the mass-fraction of low-mass (few M_{\odot}) stars exceeded $\sim 90\%$, then their early IR background radiation dominated over the LW background in suppressing H_2 formation. This low-mass fraction is comparable to those in present-day IMFs, and it is interesting to note that in this limit, star formation in minihalos could be more efficient than if the early stars were massive, owing to the lack of UV feedback and heating inside halos. The early IR background from the low-mass stars would then exert significant net feedback, and regulate the star-formation history in the early Universe once a fraction f_* = a few $\times f_{*,\text{LW}}$ of baryons were converted into stars. The threshold $f_{*,\text{LW}}$ is the fraction required for strong LW feedback (from massive stars), which is $\sim 0.3\%$ that required for reionization assuming $n_{\gamma} = 10$ ionizing photons per hydrogen atom. Future investigations of radiative feedback in the early Universe, which include low-mass stars, should therefore include H^- photo-detachment. Our results also highlight the need for an accurate calculation of the IR photon output of low-mass stars.

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